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FATIGUE RECLAMATION:
THE CONCEPT OF SELF-HEALING

E. TROIANO
P. J. COTE
G. N. VIGILANTE

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E. Troiano, P.J. Cote, and G.N. Vigilante

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13. ABSTRACT (Maximum 200 words)

A simple analytical model for predicting the onset of fatigue crack initiation has been developed. The model's usefulness is based on the premise that if a component can be removed from service before fatigue crack initiation and thermally heat-treated to remove any accumulated fatigue damage, it can be placed back in service and periodically heat-treated to extend its life.

Three-point bend specimens with semi-circular notches were machined from A723 steel, isothermally processed in molten salts to predetermined strength and toughness levels, and fatigue-tested in the extreme low cycle fatigue region.

Because of negative preliminary findings, the concept of reclamation fatigue in the extremely low cycle fatigue regime does not appear to be a viable means for extending the overall life of components. Although technically correct, the model did not accurately predict the onset of crack initiation. The study also suggests that, although cracking was not observed in all specimens, some damage could not be eliminated by thermal treatment. Because most point defects will be eliminated by thermal treatment, it is believed that non-detectable microscopic crack growth had occurred.

14. SUBJECT TERMS
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INTRODUCTION

The concept of removing cyclic damage by thermal treatment was investigated. It was speculated that if fatigue damage could be intercepted before the cracking region (e.g., while in the stage I regime), then damage could be removed and the component restored to its previous condition.

Two other areas that overlap with the focus of the analysis were also investigated. The first area focused on when fatigue cracks initiate. For example, do fatigue cracks initiate during the first cycle or when detected by some sophisticated external means? The second area explored the sensitivity of a new technique developed by Leighton[1] et al. for predicting crack initiation.

CONCEPT AND MODEL OF FATIGUE RECLAMATION

A simple model has been developed that explains how the concept of the reclamation can be used to extend the fatigue life of a component. If the premise of the theory is correct, fatigue lives can be extended indefinitely for all components and materials.

The model uses the well-known Coffin-Manson equation

$$\Delta\varepsilon_p \approx \Delta\varepsilon = \varepsilon_{f'} (2N_f)^c \tag{1}$$

for predicting life in the low cycle fatigue regime as a function of the applied plastic strain range, $\Delta\varepsilon_p$; the true fracture strain, ε_f; and the fatigue ductility exponent, c.[2] Rearranging the terms of equation [1] and adding a scaling factor, F; a confidence interval, β; and an inequality results in

$$N_{APPLIED} < F * (2N_f - \beta) = F * ([\frac{\Delta\varepsilon_p}{\varepsilon_{f'}}]^{1/c} - \beta) \tag{2}$$

The scaling factor F must be less than one to ensure that life remains in the component. $N_{APPLIED}$ is the number of applied cycles at the given $\Delta\varepsilon_p$ and F. The β term is defined as

$$\beta = 2N_f \pm (1+\alpha)(\frac{SD}{\sqrt{n}}) \tag{3}$$

where α is the confidence level, SD is the standard deviation of the test data, and n is the population. The overall life of the component, N_∞, can be written as

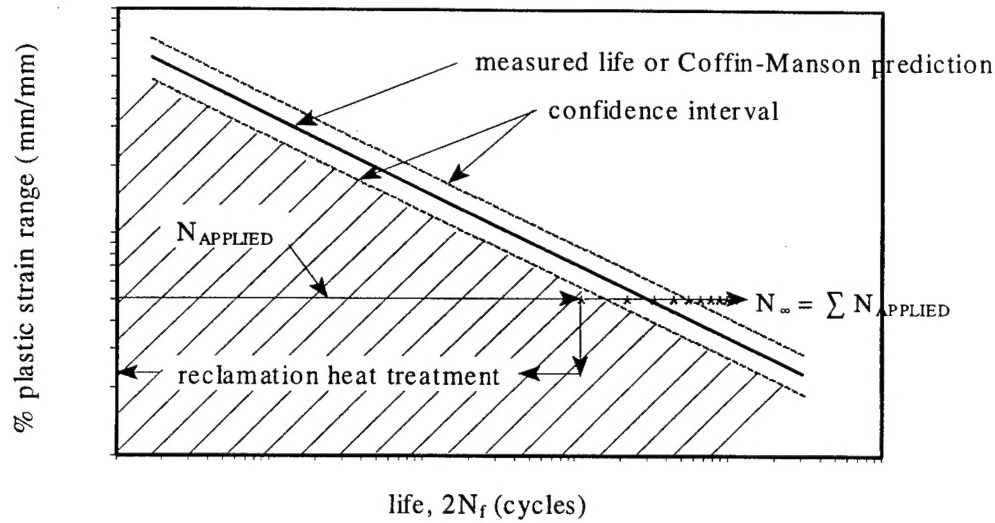$$N_\infty = \sum N_{APPLIED} \tag{4}$$

1

Figure 1. Schematic diagram of reclamation concept

Figure 1 is a schematic diagram of the model outlined in this section. The solid line represents the measured life (or the Coffin-Manson prediction of life), the dotted lines represent the $\beta\%$ confidence interval of the test data, and the cross-hatched region represents the $F*(2N_f - \beta)$ (or the $\beta\%$ probability of fatigue reclamation).

TEST SET-UP, MATERIAL, AND HEAT TREATMENT

A semi-circular notched specimen in three-point bending (Figure 2) was tested to establish where detectable crack indications were observed and if previous fatigue damage could be removed by thermal heat treatment. The material investigated was A723 Grade 2 pressure vessel quality steel (see Table 1 for typical properties); however, the reclamation concept theory is insensitive to material. Heat treatment parameters established by Barranco[3] et al. recommend a low temperature isothermal process heat treatment for A723 steel, as follows: austenitize at 830°C in molten salts for 1 hour, followed by an austemper at 250°C in molten salts for 1 hour. The isothermal process prevents scaling from occurring and maintains the dimensional stability of the component.

Table 1. Mechanical properties of isothermally processed A723 Steel

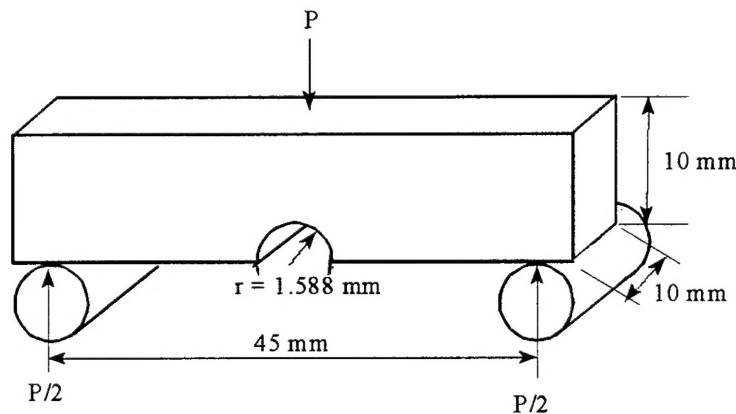| RA (%)	El (%)	0.1% YS (MPa)	UTS (MPa)	K_{Ic} (MPa$\sqrt{}$m)
52	20	779	1572	110

Figure 2. Specimen geometry and loading

Five specimens were fatigue-tested in load control to final failure in order to establish a plastic strain range versus life cycle plot in the low cycle regime. Test data for initiation and final life are shown by the filled and open symbols in Figure 3. A fatigue load of 1475 kg, which corresponds to 5177 cycles-to-failure, was selected for all subsequent testing. Five more specimens were then tested at this load for 1000, 2000, 3000, 4000, and 5000 cycles and are identified as N_{f1000}, N_{f2000}, N_{f3000}, N_{f4000}, and N_{f5000}, respectively (Figure 4). The five specimens were then wrapped in stainless steel foil wrap (to prevent damage to the notched surface in the molten salt bath) and re-isothermally heat-treated according to the heat treatment profile described earlier. This second heat treatment removes any slip bands, twinning, point defects, or other sub-microscopic damage that may have occurred during fatigue cycling and, hopefully, restores the material to its previous undamaged condition. Fatigue cycling of the five specimens was continued until final failure.

It is believed that if all traces of the initial cycling could be removed with the thermal processing, overall fatigue life would increase. This premise is based on the assumption that there is no fatigue cracking of the specimen before the second thermal heat treatment. For example, if all traces of the initial cycling of the N_{f1000} specimen were removed, then an overall life of approximately 6177 cycles (5177 cycles + 1000 cycles) would be expected. Figure 4 shows the expected lives after reclamation heat treatment and the $\beta = 99\%$ confidence interval of life at the applied plastic strain range. Because there is a 99% chance that a fatigue crack will be present in the N_{f5000} specimen, the likelihood that its life will exceed 5177 cycles is less that 1%. Thus, it is not believed that any life extension can be attained. However, for the remaining specimens, there is a 99% chance that no fatigue crack will be present and a good probability that lives can be extended.
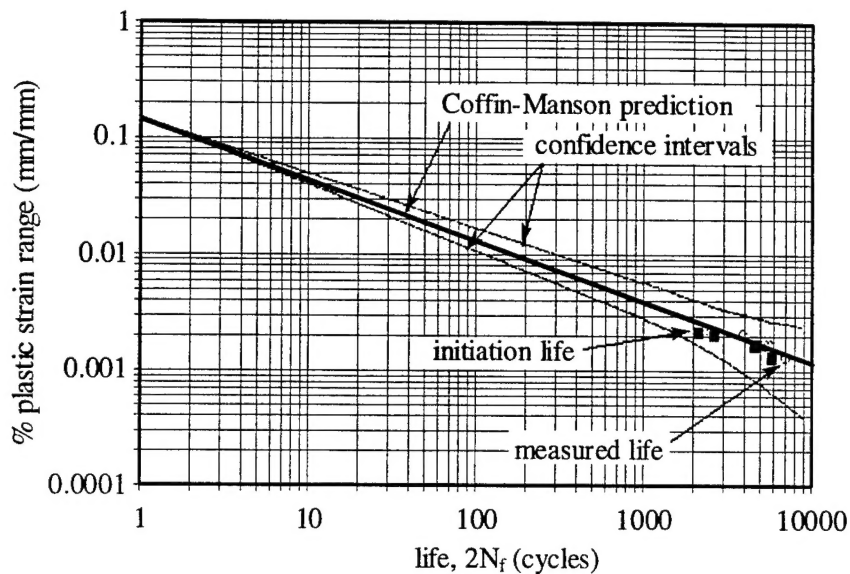
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Figure 3. % Plastic strain range versus life, A723 Steel, YS = 1,400 MPa

Crack initiation was monitored using a technique established by Leighton et al. Although not as accurate as monitoring crack indications with a clip gage, this technique does provide some indication of crack initiation and growth. This study intended to determine how sensitive this technique is in monitoring crack initiation.

TEST RESULTS

The results of the test are shown in Table 2. While testing N_{f1000} through N_{f5000}, the only specimen experiencing any indication of crack initiation was the N_{f5000} specimen (Figure 3). Because cracking had initiated in this specimen, reclaiming it by thermal treatment would not be effective. As seen in Table 2, specimen N_{f5000} had total cycles-to-failure of 5190—or 0.3% greater than the target 5177 cycles.

The other four specimens did not exhibit any positive indication of cracking during testing. However, specimen N_{f4000} was questionable. It was believed that specimens N_{f1000} through N_{f4000} should exhibit total fatigue lives ranging from 6177 cycles to 9177 cycles, respectively. Again, this is based on the premise that no fatigue cracking has initiated. As observed in Table 2 and in Figure 5, specimens N_{f1000} through N_{f4000} experienced total fatigue lives of 4200, 5000, 4750, and 5380 cycles, respectively. This was considerably different from the 6177, 7177, 8177, and 9177 cycles-to-failure that were expected. All of the specimens (with the exception of N_{f1000}) failed within the $\beta = 99\%$ confidence interval.
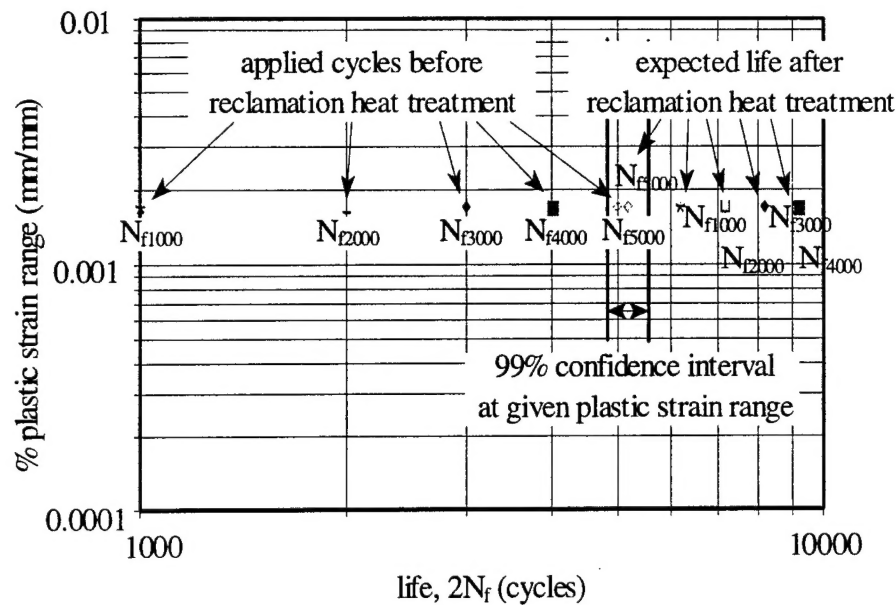
0.01

applied cycles before
reclamation heat treatment

expected life after
reclamation heat treatment

% plastic strain range (mm/mm)

N_{f1000} N_{f2000} N_{f3000} N_{f4000} N_{f5000} N_{f1000} N_{f3000}

N_{f1000}

N_{f2000} N_{f4000}

0.001

99% confidence interval
at given plastic strain range

0.0001

1000   10000

life, 2N$_f$ (cycles)

Figure 4. Applied and expected lives, A723 Steel, YS = 1,400 MPa

**Table 2. Test parameter cycle count before and after
reclamation fatigue heat-treatment**

I.D.	$N_{APPLIED}$	$F^*(2N_f)$ (%)	Crack observed	Target life expected	Life obtained	% from target	% from $2N_f$=5177
N_{f1000}	1000	19.3	no	6177	4200	-32.0	-18.9
N_{f2000}	2000	38.6	no	7177	5000	-30.3	-3.4
N_{f3000}	3000	57.9	no	8177	4850	-40.7	-6.3
N_{f4000}	4000	77.3	?	9177	5380	-41.4	+3.9
N_{f5000}	5000	96.6	yes	5177	5190	+0.3	0.3

DISCUSSION

The results reveal that fatigue cracking initiated in all of the specimens—indicating that initiation lives in this region were much lower than originally anticipated. The specimens were then inspected with a scanning electron microscope to identify fatigue crack initiation. Fatigue crack initiation was positively identified in specimens N_{f3000} through N_{f5000}—with crack indications of 0.2 mm, 0.3 mm, and 1.27 mm, respectively. Cracking had positively initiated in these specimens, and reclaiming them through thermal treatment was not effective. As seen in Table 2, specimens N_{f3000} through N_{f5000} had total cycles-to-failure of 4850, 5380, and 5190, respectively—or -6.3%, +3.9%, and +0.3% from the target 5177 cycles.
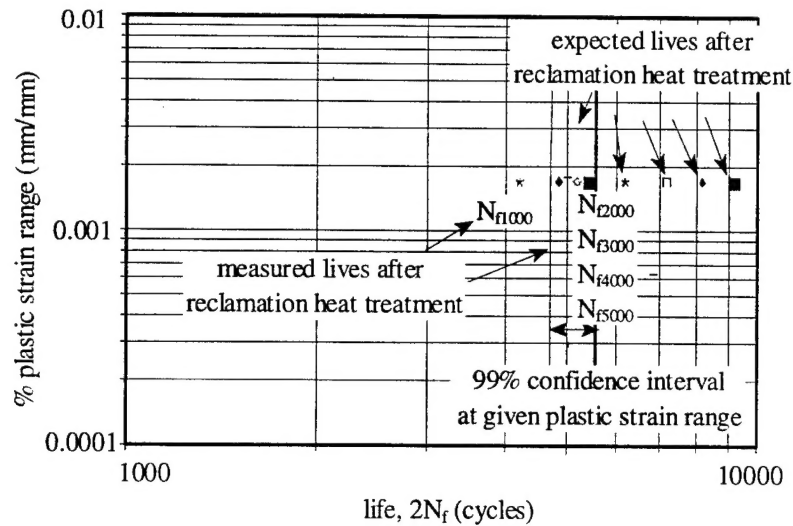
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Figure 5. Measured and expected lives A723 Steel, YS = 1,400 MPa

When inspected with the scanning electron microscope, no crack indications were observed in the N_{f1000} and N_{f2000} specimens. Thus, according to our hypothesis, the fatigue lives for these specimens should have been extended beyond the targeted 5177 cycles. However, as seen in Table 2, the total life of N_{f1000} was 4200 cycles (or 18.9% less than the target life) and N_{f2000} was 5000 cycles (or -3.4% less than the target life). Because the overall life of these specimens was less than the target life and no cracking was observed, the concept of reclaiming of a component with fatigue damage is not viable in the low cycle fatigue regime.

CONCLUSION

This study demonstrated that reclamation of a fatigue-loaded component in the extreme low cycle regime is not possible because cracks initiated much earlier than anticipated and predicted. In the extreme low cycle fatigue region, it appears that more life is consumed in crack propagation than in crack initiation.

Cracks of less than 0.3 mm went undetected with the technique developed by Leighton et al. However, the technique did detect cracks greater than 0.3 mm. The failure to prove whether reclamation is a viable means of extending the life of a component depends on crack detection. It is obvious that a more accurate means of detecting crack initiation is necessary.

Continuation of this work will investigate reclamation fatigue with longer fatigue lives. It is felt that if fatigue damage occurs in a region (even in stage I) where crack initiation dominates over crack propagation, then reclamation may be possible.

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REFERENCES

1. Leighton, D. E., Abbott, R. T., "A Simple and Accurate Technique for Monitoring Crack Growth Behavior with a Waveform Analyzer," ARDEC Technical Report ARCCB-TR-95001, Benet Laboratories, Watervliet, NY, January 1995.

2. Troiano, E., Underwood, J. H., and Crayon, D., "Low Cycle Notched Fatigue Behavior and Life Predictions of A723 High Strength Steel," *ASME/JSME*, PVP, Vol 306, pp. 179-190.

3. Barranco, J. M., Cote, P. J., and Kapp, J. A., "Tempering Effects for Lower Bainite, Martensite, and Mixed Microstructures on Impact, Fracture, and Related Mechanical Properties for ASTM A723 Steel," ARDEC Technical Report ARCCB-TR-92024, Benet Laboratories, Watervliet, NY, June 1992.

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